beverages

Review

Development of Functional Fruit, Vegetable, and Herbal Beverages Enriched with Gamma-Aminobutyric Acid and Polyphenols: Is It Feasible?

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Abstract

Polyphenols and gamma-aminobutyric acid (GABA) are diet-derived bioactive compounds with distinct yet complementary health benefits. Polyphenols exert strong antioxidant and anti-inflammatory effects, whereas GABA serves as an inhibitory neurotransmitter that supports neurological balance. Functional beverages enriched with both compounds based on fruits, vegetables, and herbs, therefore, hold considerable potential for promoting health. However, formulating such products presents substantial challenges. Fruits, vegetables, and herbs are typically rich in polyphenols but low in GABA, while GABA-rich foods often contain minimal polyphenols. Analysis of available data on the polyphenol and GABA content of such beverages revealed substantial variability, underscoring the need for greater standardization. To provide a clearer framework for this review, functional beverages were defined as effective sources of these bioactives if they deliver at least 200 mg of GABA and 500 mg of polyphenols per single daily serving. However, none of the reviewed studies met both criteria, highlighting the need for an integrated approach to develop beverages capable of supplying meaningful amounts of each compound. While fermentation, particularly with lactic acid bacteria, can substantially increase GABA levels, selecting antioxidant-rich fruits and herbs naturally high in polyphenols remains essential. Together, these approaches offer a viable pathway for creating multifunctional beverages with enhanced health value and may help meet the growing demand for natural, functional, health-promoting products.

Keywords: functional beverages; polyphenols; gamma-aminobutyric acid (GABA); biofortification; fermentation; lactic acid bacteria

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1. Introduction

Over the past several decades, gamma-aminobutyric acid (GABA) has become the subject of great interest because of its widespread distribution in nature. GABA is present in almost all living organisms, including plants, animals, and microorganisms, where it plays vital physiological roles and provides promising health benefits [1]. GABA is a non-protein amino acid that serves as the principal inhibitory neurotransmitter in the mammalian central nervous system. Beyond its physiological role, GABA has been investigated for a

range of pharmacological effects. Studies report its potential to lower blood pressure [2], contribute to diabetes prevention [3], and modulate cholesterol levels [4]. Additional pharmacological activities attributed to GABA include anxiolytic, stress-reducing, and sleep-enhancing effects [5]. GABA intake has also been explored for therapeutic relevance in neurological disorders such as seizures, Parkinson's disease, stiff-man syndrome, and schizophrenia [6]. Further reported pharmacological actions encompass the inhibition of cancer cell proliferation [7] and protection against heat-induced stress [8]. Based on the information presented so far, GABA is recognized as an essential nutrient suitable for the development of nutraceuticals and functional foods.

Polyphenols represent one of the most abundant and widely distributed classes of bioactive compounds in the plant kingdom. To date, over 8000 distinct phenolic structures have been identified in nature, all characterized by the presence of one or more phenolic groups. Polyphenols comprise a structurally diverse group of phytochemicals encompassing multiple subclasses, including phenolic acids, flavonoids, and proanthocyanidins. These naturally occurring pigments are abundant in vividly colored plant matrices, including fruits, vegetables, and flowers, and are responsible for their characteristic coloration [9]. They are recognized as potent natural antioxidants, capable of neutralizing free radicals and thereby mitigating oxidative stress. This activity plays a crucial role in the prevention of various chronic and inflammation-related diseases, such as cardiovascular disorders, cancer, and neurodegenerative conditions [9]. Among polyphenols, flavonoids have been associated with protective effects against metabolic diseases, including obesity and type 2 diabetes [10]. Specifically, the anthocyanin cyanidin-3-*O*-glucoside has demonstrated neuroprotective effects against ischemic stroke [11] and is implicated in the prevention of atherosclerosis. Additionally, anthocyanin-rich bilberry extract has been shown to significantly reduce plasma total cholesterol and hepatic triglyceride levels [12]. Polyphenols also act as metal chelators and, by binding transition metals such as Fe^{2+}, they inhibit the Fenton reaction, thereby preventing the formation of highly reactive hydroxyl radicals [13,14]. Furthermore, polyphenols enhance endogenous antioxidant defense systems by stimulating enzymes such as glutathione peroxidase, catalase, and superoxide dismutase, while concurrently downregulating pro-oxidant enzymes like xanthine oxidase [15]. They also contribute to the regeneration of essential vitamins, enhancing the body's overall antioxidant capacity [16]. Although polyphenols are commonly found in nuts, seeds, legumes, and cereals, their levels are considerably higher in beverages such as tea infusions, cocoa, coffee, and wine [17]. Interestingly, fermentation processes can enhance polyphenol content, as demonstrated in fermented products such as kombucha [18].

The food industry has witnessed a growing demand for functional beverages and foods, which not only offer basic nutritional benefits but also provide health-promoting effects. The concept of 'functional food' was first introduced in 1993 in the publication 'Japan explores the boundary between food and medicine' [19]. Functional foods are defined as foods that extend beyond basic nutritional value by providing additional physiological benefits and potentially reducing the risk of non-communicable diseases. Fruits and vegetables represent the simplest type of functional foods because they naturally contain bioactive compounds such as antioxidants and polyphenols. Nowadays, functional foods are introduced across most food categories in response to changing consumer preferences. Among these, dairy, bakery, soft drinks, pastry, and baby food contain the greatest variety of functional foods. Functional beverages, in particular, have gained considerable attention and constitute the fastest-growing segment of the beverage industry, with an average annual consumption of 250 L per person reported in 2006 [20]. They are often preferred over functional foods because beverages can more easily deliver health-promoting compounds, offer better flavor profiles, and are typically consumed in larger quantities [20].

A functional beverage can be defined as a non-alcoholic drink enriched with bioactive components derived from plant-based, animal-based, marine-based, or microbial sources, which contribute to improving human health. Examples include dairy drinks, energy and sports drinks, fortified teas, kombucha, smart beverages, plant-based milks, and nutrient-enriched waters [21]. Functional beverages may provide a wide range of health benefits. For instance, dairy-based drinks containing probiotics can improve stomach and colon function. Plant-based beverages enriched with antioxidants may help prevent cancer, cardiovascular diseases, neurological conditions, and neurodegenerative disorders, while also enhancing immune function and exhibiting anti-aging effects. Similarly, functional fruit juices are developed by fortifying regular juices with bioactive compounds such as carotenoids, phenolic acids, flavonoids, fatty acids, probiotics, prebiotics, minerals, and vitamins [21]. Some examples of functional beverages include orange juice fortified with vitamin C, calcium, and phytosterols, berry drinks with anthocyanins, and green tea enriched with epigallocatechin gallate (EGCG) [22].

A substantial body of evidence indicates that the health benefits of fruit and vegetable beverages are largely attributable to their polyphenolic constituents and associated antioxidant properties. Several fruit-based beverages have demonstrated antioxidant and metabolic benefits in humans, including improvements in glycemic control, reductions in oxidative stress, and enhanced serum antioxidant capacity [22–27]. In contrast, evidence on GABA-enriched beverages remains limited. GABA-fortified Oolong tea has been reported to improve heart rate variability and reduce stress [28], while daily intake of fermented milk providing 12.3 mg GABA for 12 weeks produced modest reductions in systolic and diastolic blood pressure, though values remained above normal limits [29].

In summary, the consumption of plant-based beverages could provide both therapeutic and preventive health benefits. In particular, functional beverages enriched with GABA and polyphenols hold significant promise for promoting health through their combined antioxidant, anti-inflammatory, and neuroprotective properties. Therefore, this review aims to analyze available data on the GABA and polyphenol content of fruit-, vegetable-, and herb-based beverages and to identify ingredients and approaches that support the formulation of products capable of delivering meaningful levels of both compounds in a single daily serving. By integrating polyphenol-rich components with GABA-enhancing techniques, this review seeks to identify pathways for creating multifunctional beverages with synergistic health benefits. Ultimately, it highlights the potential of such formulations to meet the growing consumer demand for natural, health-promoting functional beverages.

2. Daily Intake of GABA and Polyphenols

Available clinical trials employing either the pure compound or fermented GABA-enriched foods (10–120 mg GABA/day) have consistently demonstrated hypotensive and fatigue-reducing effects of GABA, with no reports of severe adverse events [29–34]. Moreover, GABA is regarded as highly safe and exhibits minimal toxicity, even when administered at markedly elevated pharmacological doses. For instance, daily consumption of 5 g GABA has been shown to modulate growth hormone and prolactin secretion in humans via dopamine release at a suprapituitary level, without eliciting serious side effects [35–37]. Similarly, another clinical study administering up to 6 g/day (2 g three times daily for seven days) documented rapid absorption and enhanced islet hormone secretion, again in the absence of significant adverse reactions [38]. Collectively, these findings substantiate both the physiological benefits of GABA and its robust safety profile.

Information on habitual dietary GABA intake in humans remains limited. One recent study estimated that a balanced daily diet rich in fruits and vegetables provides approximately 740 mg of GABA per day, derived predominantly from vegetables (~500 mg) and

fruits (~20 mg), with potatoes accounting for more than 56% of the total intake [39]. In contrast, another investigation assessing GABA intake from a nutritionally controlled hospital diet reported substantially lower values, with analyzed and calculated median daily intakes of 67.3 mg and 30.0 mg, respectively [40]. Although regulatory upper limits for daily GABA intake have not been formally established, the NNHPD monograph for Cognitive Function Products recommends a daily intake of 50–3000 mg GABA, not exceeding 750 mg per single dose [41]. The monograph further advises consultation with a healthcare practitioner when consuming more than 300 mg/day for periods longer than four weeks [42]. Taken together, these data indicate that the predefined daily dose of 200 mg GABA in our study is both safe and nutritionally relevant.

Compared to GABA, the average daily intake of polyphenols has been more extensively studied and varies greatly across populations. For example, the European Prospective Investigation into Cancer and Nutrition (EPIC) study reported that mean total polyphenol intake in Europe was highest in Aarhus, Denmark (1786 mg/day in men and 1626 mg/day in women) and lowest in Greece (744 mg/day in men and 584 mg/day in women), with phenolic acids representing the major contributors (52.5–56.9%) and coffee, tea, and fruits identified as the primary food sources [43]. In Poland, the mean polyphenol intake was 1756.5 ± 695.8 mg/d (median = 1662.5 mg/d). The individual compounds with the highest intakes were isomers of chlorogenic acid that largely originated from coffee, and catechins mostly originating from tea and cocoa products [44]. A recent study estimated that the daily intake of phenolic compounds in elderly Japanese varied significantly among individuals (183–4854 mg/day), and was attributable mostly to beverage consumption. Their average total polyphenol intake was 1492 ± 665 mg/day, the greatest part of which was provided by beverages-coffee (43.2%) and green tea (26.6%) were the major sources of total polyphenols [45]. In the United States, a 10-year analysis revealed a mean intake of 884 mg per 1000 kcal/day (equivalent to 1768 mg/day for a 2000 kcal diet), with major contributors including coffee (39.6%), beans (9.8%), and tea (7.6%) [46]. Reported median polyphenol intakes include 364.3 mg/day in Brazil [47] and 1673 mg/day in the Czech Republic, where non-alcoholic beverages such as coffee, tea, and juices were the dominant sources, followed by fruits, cereals, and vegetables [48].

As outlined in this section, the most significant dietary sources of GABA are vegetables (particularly potatoes and tomatoes), while caffeine-containing beverages such as coffee and tea are the primary sources of polyphenols. For the purposes of this review, we define functional beverages as effective sources of these bioactives if they provide at least 200 mg of GABA and 500 mg of polyphenols per single daily serving. Although these thresholds are somewhat arbitrary, they are informed by available evidence on typical dietary intakes and represent levels that may plausibly confer health benefits while remaining compatible with a balanced diet. Furthermore, the inclusion of GABA and polyphenols should be achieved through natural ingredients and processing techniques rather than through fortification with isolated compounds. To ensure broad consumer suitability, such beverages should also contain zero or minimal amounts of caffeine, alcohol, alkaloids, or other stimulatory substances.

3. Polyphenol and GABA Content in Fruit and Vegetable Juices and Beverages

3.1. Polyphenol and GABA Content in Fruits and Vegetables, Suitable for Preparation of Beverages

Identifying plant sources naturally rich in GABA could be essential for developing functional beverages that deliver meaningful health benefits without relying on synthetic additives. GABA is present in nearly all plants, including fruits, vegetables, legumes, cereals, herbs, spices, and algae. Its concentration varies depending on species and variety,

environmental conditions, agricultural stress, and post-harvest processing. The accumulation of this amino acid can be induced by both biotic and abiotic stress factors [1,49], yet its levels in commonly consumed foods are generally low [50].

Among plant sources, vegetables typically exhibit the highest GABA concentrations, with tomatoes and potatoes being particularly notable. Potatoes were the first vegetables reported to contain GABA [51], and their levels vary across different tissues [52]. Reported concentrations in potatoes range from 16 to 61 mg per 100 g fresh weight (FW), and up to approximately 300 mg per 100 g dry weight (DW) [52,53]. In tomatoes, GABA content ranges from 8.8 to 189.7 mg per 100 g FW [54]. Other vegetables rich in GABA are cabbage (188 mg/100 g) [55], beetroot (18.8 mg/100 g FW), green pepper (10.6 mg/100 g FW), and broccoli (12.9 mg/100 g FW) [50]. Among fruits, lychee is considered the richest in GABA, with concentrations ranging from 170 to 350 mg/100 g FW, which is nearly 100 times higher than in most other fruits [56]. Jujube also contains high GABA levels (140 mg/100 g DW) [57]. Citrus fruits are widely used in beverages and are rich in antioxidants, but their GABA content remains low [58]. Blueberries, though high in polyphenols and anthocyanins [59], also contain relatively little GABA (7.9 mg/100 g FW) [60]. Among berries, mulberries exhibit the highest GABA levels, ranging from 86.1 to 185.6 mg/100 g DW across seven varieties [61], whereas black raspberry (19.4 mg/100 g FW), raspberry (10.1 mg/100 g FW) [60], and European gooseberry (13.2 mg/100 g FW) show only moderate levels. Other polyphenol-rich berries (black currant, elderberry, and black chokeberry) also contain very low amounts of GABA—5.4, 4.6, and 2.4 mg/100 g FW, respectively [50].

The polyphenol content of fruits and vegetables has been extensively studied, and numerous reports describe their total polyphenol levels. Berries and other fruits with purple pigmentation are particularly notable for their high polyphenol concentrations and strong antioxidant activity, making them attractive candidates for functional beverage development [62]. A wide range of fruits is commercially processed into juices and nectars, including citrus fruits (orange, lemon, grapefruit, tangerine), berries (chokeberry, elderberry, cranberry, blueberry, mulberry), apples, pears, apricots, peaches, grapes, and plums, among others. Among these, chokeberry is distinguished as one of the richest polyphenol sources, with reported levels ranging from 719 to 6902 mg/100 g FW, and demonstrates exceptionally high antioxidant capacity compared with other fruits [63]. Other fruits with substantial polyphenol content include European gooseberry and elderberry, with concentrations reaching up to 2611 mg/100 g FW and 1540 mg/100 g FW, respectively [64,65]. In general, vegetables are not as rich a source of phenolic compounds as fruits, and with a few exceptions (tomato, beetroot, carrot), are less suitable for juice production. Among vegetable sources, beetroot shows moderate polyphenol content, reaching up to 255 mg GAE/100 g FW [66]. Broccoli also contains appreciable levels of phenolic compounds, with reported concentrations ranging from 48.15 mg/100 g FW [67] to 290 mg/100 g FW [65]. Carrot, which is widely used in beverages due to its favorable sensory properties, contains between 9.8 and 61.9 mg/100 g FW, with purple varieties reaching up to 342.2 mg/100 g FW [68,69].

3.2. Polyphenol and GABA Content in Fruit and Vegetable Juices

The composition of fruit and vegetable juices often differs from that of the edible raw materials. Therefore, Table 1 summarizes the available data for GABA and polyphenol contents in fruit and vegetable beverages, obtained from raw materials suitable for beverage production. Data are presented in descending order based on GABA content, and for easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/L.

Table 1. GABA and polyphenol content of fruit and vegetable juices and beverages.

Raw Material	Latin Name	GABA Content, mg/L	Polyphenol Content, mg/L	References
Tomatoes (raw juice)	*Lycopersicon esculentum Roma VF*	4220	396.4–421.9	[70,71]
Lychee (pasteurized juice) (cloudy fresh juice)	*Litchi chinensis*	887.5 nd	620 >500	[72,73]
Orange (commercial juice) (Fresh juice)	*Citrus ×sinensis*	240–320 180–500	840.6 548–1407	[58,74–76]
Grapefruit (fresh juice)	*Citrus paradisi*	180–570	1173–2216	[74,76]
Tangerine juice (fresh juice)	*Citrus reticulata*	150–500	36.6–132.6	[74,77]
Broccoli (fresh juice)	*Brassica oleracea var. italica*	90.75–509.4	929.2	[78,79]
White mulberry (fresh juice)	*Morus alba* L.	66.2–98.7	nd	[80]
Black currant (fresh juice) (commercial juices)	*Ribes nigrum*	62.9–140.2	6800	[81,82]
Lemon (Fresh juice)	*Citrus limon*	70 60–185	658–1538	[58,74,76]
Red currant juice (fresh juice)	*Ribes rubrum*	48.5–151.6	1330	[81,83]
Persimmon (purees) (pasteurized juice)	*Diospy ros kaki var. Sharoni*	36.6	303.58	[84,85]
Grape juice (commercial juice)	*Vitis vinifera*	34.8	400–3000	[86,87]
Peach (commercial and fresh juice)	*Prunus persica* L.	30.2–130.2	63.6	[88,89]
Black chokeberry, (commercial), (fresh juice)	*Aronia melanocarpa*	6.68	9154	[63,90]
Apple (commercial juice), (fresh juice)	*Malus domestica* *Malus pumila P. Mill.*	5.2	154–178	[86,91]
Strawberry (commercial puree)	*Fragaria × ananassa*	2.2–34.9	1406	[75,84]
Cucumber (fresh juice)	*Cucumis sativus*	2.1–19.6	532.7 mg/L	[78,92]
Radicchio (fresh juice)	*Cichorium intybus var. foliosum*	2.1–4.1	nd	[78]
Black mulberry (fresh or pasteurized juice)	*Morus atropurpurea* Roxb	nd	412.55–3210	[93,94]
Black raspberry (fresh juice)	*Rubus occidentalis*	nd	640	[95,96]
Elderberry (fresh juice)	*Sambucus nigra*	nd	2160–8590	[97]
Blueberries (commercial juice concentrate)	*Vaccinium sect. Cyanococcus* *Vaccinium myrtillus* L. *wild*	nd	3845	[75]
Pineapple (fresh juice)	*Ananas comosus*	nd	10.6	[89]
Pear (pasteurized juice)	*Pyrus communis*	nd	7735	[85]

nd—not determined. For easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/L.

The data reveal that raw tomato juice has the highest GABA content, with a value of 4220 mg/L [70], which is approximately ten times higher than the average GABA content found in fruit and vegetable juices. However, its polyphenol content is moderate—about 400 mg/L. Lychee juice is another beverage that serves as a good source of GABA (887.5 mg/L), and similarly to tomato juice, it contains moderate polyphenol levels (>500 mg/L) [72,73]. However, this amount cannot provide 200 mg of GABA per 200 mL serving. Citrus juices contain low to moderate GABA levels and are therefore unsuitable as sole GABA sources. All other reviewed juices likewise contain only small amounts of GABA. In contrast, several juices are exceptionally rich in polyphenols yet relatively poor in GABA. For example, black chokeberry juice contains more than 9000 mg/L of polyphenols but only 6.7 mg/L of GABA [98]. Other juices that supply substantial quantities of polyphenols include grapefruit, black currant, elderberry, blueberry, and pear.

In conclusion, fruit and vegetable juices with the highest GABA concentrations tend to be comparatively low in polyphenols, whereas polyphenol-rich juices generally contain little GABA. Based on predefined daily intake targets, only tomato juice can deliver 200 mg of GABA in a single 200 mL serving and, in fact, this dose could be achieved with a much smaller quantity (approximately 20–30 mL). Nevertheless, several other juices are excellent sources of polyphenols, creating opportunities for developing mixed beverages by blending GABA-rich juices (e.g., tomato and lychee) with polyphenol-rich juices (e.g., black chokeberry, black currant, elderberry, blueberry). Such formulations could provide both 200 mg of GABA and 500 mg of polyphenols in a single serving. Overall, these findings highlight the importance of selecting appropriate plant sources when formulating GABA-enriched beverages.

4. Polyphenol and GABA Content in Medicinal Plants and Herbal Infusions

4.1. Polyphenol and GABA Content in Medicinal Plants

Beyond fruits and vegetables, medicinal plants represent a rich source of phytochemicals with well-documented health benefits and are widely used as raw material for the production of functional beverages. Herbs and spices contain numerous bioactive constituents, including polyphenols, polysaccharides, vitamins, minerals, and alkaloids, which can contribute to a range of beneficial physiological effects [99]. The use of medicinal plants for culinary and medicinal purposes in the form of herbal beverages has a long history and has significantly increased in modern times. Herbal drinks are abundant in compounds such as phenolic acids, flavonoids, terpenoids, carotenoids, coumarins, alkaloids, saponins, etc. These constituents have been shown to exhibit strong antioxidant, antibacterial, antiviral, anti-inflammatory, anticarcinogenic, antiallergic, antithrombotic, antimutagenic, and antiaging properties [21]. Herbal beverages are classified as natural health products, and consumption of 2–3 cups per day of selected teas, such as those containing citrus peel, lemon balm, ginger, orange peel, and rosehip, is considered beneficial during pregnancy and lactation [100]. They are prepared mainly by infusing or boiling fresh or dried flowers, immature fruits, leaves, seeds, and roots. Green tea (*Camellia sinensis*) is the world's most commonly consumed beverage. The pharmacological properties of tea encompass antioxidant, antimutagenic, antiproliferative, anticarcinogenic, and neuroprotective activities. Representing over 40% of the total catechin content in green tea leaves, EGCG is widely recognized as the primary bioactive component responsible for green tea's potent antioxidant effects. Rooibos (*Aspalathus linearis*), characterized by a high ascorbic acid content and low tannin levels, is widely recognized for its health-promoting properties, including antioxidant, antimutagenic, hepatoprotective, phytoestrogenic, and antidiabetic effects. Observational studies have shown that the consumption of herbal teas made from medicinal plants, including species lavender, chamomile, spearmint, echinacea, hibiscus, fenugreek, nettle, and yerba maté, as well as herbal combinations, provides numerous health benefits. They are used to support female health, help regulate blood glucose levels, improve cardiovascular function, promote weight loss, enhance liver health, etc. [101]. Table 2 summarizes the available data on the GABA and polyphenol content of medicinal plants commonly used to prepare infusions. Data are presented in descending order based on GABA content.

Table 2. GABA and polyphenol and content in medicinal plants.

Raw Material	Latin Name	GABA Content, mg/100 g	Polyphenol Content, mg/100 g	References
Passiflora	*Passiflora incarnate* *Passiflora quadrangularis* *Passiflora edulis*	629	1030–3740	[102,103]
Ginseng (root, fresh)	*Panax ginseng*	322	721–3021	[102,104]
Echinacea	*Echinacea purpurea*	249	141–19,570	[102,105,106]
Hibiscus	*Hibiscus sabdariffa*	>102	66.1	[107,108]
Vine	*Ampelopsis grossedentata*	>102	17,725	[107]
Isodon	*Isodon serra*	>102	9784	[107]
Valeriana (root)	*Valeriana officinalis*	85	1454–3316	[102,109]
Ginkgo biloba	*Ginkgo biloba* L.	77	1515–4518	[109,110]
Bistort (roots)	*Polygonum bistorta* L.	57.3	2569–15,216	[50,111]
Chamomile	*Matricaria chamomilla*	51.4	2689	[50,112]
White tea	*Camellia sinensis*	50.5	16,230–25,950	[113,114]
Lophanthus	*Lophanthus anisatus*	49.3	7048.13	[50,115]
Parsley	*Petroselinum crispum*	28.2	1740	[50,116]
Basil	*Ocimum basilicum*	26.9	2960	[50,117]
While oregano	*Origanum vulgare*	19.8	7900–14,700	[50,118]
Spearmint	*Mentha spicata*	17.0	1188–14,262	[50,119]
Green tea	*Camellia sinensis*	10.5	8007	[107,120]
Black tea	*Camellia sinensis*	7–55	6060–22,250	[121,122]
Black tea	*Camellia sinensis*	5.5	3977	[107,120]
Green tea	*Camellia sinensis*	5–87	2872	[121,122]
Jasmine green tea	*Camellia sinensis*	2.5	8405	[123,124]

For easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/100 g.

As shown in Table 2, except for certain herbs (Passiflora aerial parts, ginseng root, and echinacea), most medicinal plants are not particularly rich in GABA. However, they are generally much richer in phenolic compounds. For example, small amounts of herbal materials, such as teas from *Camellia sinensis*, spearmint, oregano, bistort, or vine leaves, can contribute substantial quantities of phenolics, making them valuable fortifying agents for a functional beverage.

4.2. Polyphenol and GABA Content of Herbal Infusions

Medicinal plants are traditionally consumed not in their dried or fresh form, but mainly as infusions prepared by brewing several grams (usually 2~4 g) of tea leaves per serving of the herb in a much larger volume of water. This limits their consumption in high amounts, thus limiting their potential as GABA and polyphenol sources. Table 3 presents data for GABA and polyphenol content in herbal infusions. Data are presented in descending order based on GABA content. For easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/L.

Table 3. GABA and polyphenol content in herbal infusions.

Raw Material	Latin Name	GABA Content, mg/L	Polyphenol Content, mg/L	References
Darjeeling (black) English Breakfast (black) Bancha (green) Gyokuro (green) Sencha (green)	*Camellia sinensis*	16.01–37.05 (1:50)	nd	[125]
Chamomile flowers	*Matricaria chamomilla*	0.81 (1:40)	40–345 (1 pack:200 mL)	[126,127]
Lemon balm leaves	*Melissa officinalis*	0.61 (1:40)	252.3–1436 (1:33)	[126,128,129]
Hop cones	*Humulus lupulus*	0.44 (1:40)	nd	[126]
Sage leaves	*Salvia officinalis*	0.33 (1:40)	509–880 (1:33)	[126,128]
Lavender flowers	*Lavendula officinalis*	0.22 (1:40) *	500 (1:20)	[126,130]

* Solid-to-liquid ratio for preparation of infusions. nd—not determined. For easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/L.

As shown in the results, most herbal infusions contain very low and likely nutritionally insignificant amounts of GABA, typically not exceeding 1 mg/L. Only *Camellia sinensis* infusions exhibit somewhat higher GABA levels, although these still remain far below the predefined target of 200 mg per 200 mL serving. In contrast, several infusions, such as sage and lemon balm, are rich in phenolic compounds, but again cannot independently provide more than 500 mg of polyphenols per serving.

Based on the data presented in Tables 2 and 3, it can be concluded that small additions of medicinal plants (commonly 2–4 g) can substantially increase the overall polyphenol content of fruit beverages, particularly those already rich in GABA, thereby enhancing antioxidant capacity and nutritional value without requiring large quantities of plant material. From a sensory perspective, judicious selection of plant species can add aroma and help mask undesirable bitter or astringent notes, improving the overall palatability of fruit-based functional beverages. Studies on beverage fortification show that low-level botanical additions enhance perceived complexity and consumer acceptability when properly balanced, whereas excessive inclusion can diminish liking due to heightened astringency [131]. Furthermore, at these typical inclusion levels, herbs have been shown to markedly improve color intensity and anthocyanin stability through copigmentation via noncovalent stacking and hydrogen-bond interactions, thereby reducing pigment degradation during storage [132]. Because the efficacy of copigmentation depends on factors such as the copigment-to-anthocyanin ratio, pH, and temperature, formulation optimization is essential to maximize color benefits while preventing off-flavors. Overall, the incorporation of medicinal plants can enrich fruit beverages to the desired polyphenol content, enhance flavor and palatability, and improve color stability.

5. Fermented Beverages as a Source of GABA and Polyphenols

5.1. GABA Production in Fermented Plant Beverages by Lactic Acid Bacteria

The growing demand for GABA in food applications has stimulated commercial interest in its microbial production, since as highlighted in previous sections, plants generally contain low concentrations of this compound. Microorganisms, including yeasts, fungi, and

bacteria, are recognized as significant natural producers of GABA, with lactic acid bacteria (LAB) being particularly important due to their strong glutamate decarboxylase (GAD) activity and their Generally Recognized as Safe (GRAS) status [133,134]. Among LAB, *Lactiplantibacillus plantarum*, *Levilactobacillus brevis*, *Lacticaseibacillus paracasei*, *Lactobacillus delbrueckii* subsp. *bulgaricus*, *Lactobacillus helveticus*, and *Limosilacobacillus fermentum* are particularly efficient GABA producers [133,134]. Other contributing genera include *Leuconostoc*, *Pediococcus*, *Propionibacterium*, *Enterococcus*, and *Weissella* [135]. Many of these LAB strains, often isolated from fermented foods and beverages, are increasingly used to develop GABA-enriched functional products with health benefits [135,136]. Beyond their ability to synthesize GABA, LAB and their metabolites contribute to improved food safety and quality by inhibiting spoilage microorganisms and foodborne pathogens. GABA biosynthesis in LAB occurs via the α-decarboxylation of glutamate, catalyzed by the enzyme GAD, which requires pyridoxal-5′-phosphate (PLP) as a cofactor. Key GABA-producing strains include *L. brevis*, *L. plantarum*, *L. paracasei*, and *Lactococcus lactis* [137].

The increasing popularity of GABA-enriched beverages is largely driven by advancements in microbial fermentation, particularly through the use of LAB [138]. The process of microbial fermentation has emerged as a highly effective and natural method for producing GABA-enriched beverages [139]. LAB fermentation not only enhances the nutritional profile of beverages but could also improve their taste, texture, and shelf life through the production of beneficial metabolites, including GABA [140,141]. Table 4 summarizes the available studies on the use of different microorganisms for the fermentation of different beverages to obtain GABA-enriched fermented beverages.

Table 4. GABA and polyphenol content in fermented plant-based beverages.

Fermented Beverage	Microorganisms	GABA Content, mg/L	Polyphenol Content, mg/L	Reference
strawberry juice	*L. brevis*	27,019	nd	[142]
black raspberry juice	*L. brevis*	26,500	nd	[94]
aronia extract (10% juice)	*L. plantarum*	10,400	312.54	[143]
germinated pigeon pea	*L. plantarum*	5600	nd	[144]
tomato juice	*L. plantarum*	4228	293–473	[145]
lychee juice	*L. brevis*	327–3070	95–105	[146]
lychee juice	*L. plantarum*	1340	710	[72]
apple juice	*S. cerevisiae*	898.35	nd	[147]
fermented soymilk	*L. plantarum* *S. thermophilus*	552	nd	[148]
grape must	*L. plantarum*	498.05	nd	[149]
brown rice milk	*L. pentosus*	143	152.3	[150]
mature coconut water	*L. plantarum*	128	134	[151]
sugar cane juice	*Lc. lactis*	80	nd	[152]
kombucha	*A. xylinum* *Gluconobacter* spp. *S. cerevisiae*	36.5	1360.6	[153]
kombucha	*A. pasteurianus* *L. plantarum* *S. cerevisiae*	2.2	nd	[154]

nd—not determined. For easier comparison, the original GABA and polyphenol values have been recalculated and expressed in mg/L.

It is evident that a wide range of microorganisms has been employed in the development of GABA-enriched fermented beverages, and that the GABA-producing capacity of microbial strains is strongly influenced by culture conditions and substrate composition. Notably, several studies report the development of GABA-enriched beverages with exceptionally high GABA concentrations. For example, using two different *L. brevis* strains, strawberry and black raspberry juices were fermented to GABA levels exceeding 26,500 mg/L [94,142]. Although these studies did not report polyphenol levels, Section 3.1 demonstrates that strawberry and black raspberry juices contain only moderate amounts of polyphenols, which alone cannot provide 500 mg per serving. However, the first study used a very high dose of MSG (267 mM ≈ 49 g/L, ≈4.9%) for bioconversion in GABA, together with yeast extract, whereas the second used 2% MSG for the aim. In another study, *Aronia melanocarpa* extract (10% juice in water) fermented with *L. plantarum* yielded a high GABA concentration (10,400 mg/L), although lower than the aforementioned values. Again, the beverage was fermented using 2% MSG, together with 1% yeast extract and 1% skim milk. It also contained moderate phenolic levels due to the use of diluted extract rather than whole juice [143]. Additional examples include a germinated pigeon pea beverage reaching 5600 mg/L GABA [144] and GABA-enriched tomato juice containing 4228 mg/L GABA [145], both fermented again with *L. plantarum* strains. Collectively, these studies clearly demonstrate the efficacy of fermentation for producing GABA-biofortified beverages capable of delivering 200 mg of GABA in volumes far below 200 mL. However, an important consideration is that these GABA-enriched products were developed by adding MSG (typically at 1–2%) as a precursor. While no maximum level of MSG is specified for fruit juices under EU legislation, some general food categories impose limits of 10 g/kg [155]. Complete bioconversion of MSG can theoretically yield very high GABA concentrations; for instance, a 2% MSG solution could produce approximately 12,000 mg/L of GABA. Yet any residual MSG remaining after fermentation would be carried into the final product, which is undesirable for functional beverages positioned as naturally GABA-enriched. Therefore, if MSG is used, formulations must be optimized to achieve near-complete conversion. In this case, MSG supplementation during fermentation as low as 0.2–0.4% (2–4 g/L) would provide meaningful amounts of GABA to achieve 200 mg per serving. This is critical for maintaining both consumer trust and the clean-label qualities expected of GABA-enriched functional beverages.

Interestingly, fermented strawberry juice contains 26,500 mg/L of GABA, a concentration substantially higher than that achieved in fermented tomato juice (4228 mg/L), even though Section 3.1 and Table 1 show that tomato juice is naturally a much richer source of GABA than strawberry juice. This apparent discrepancy likely arises because the GABA levels reported for tomato juice correspond to its natural, non-fermented content, whereas the much higher values in strawberry juice were obtained after fermentation with a highly efficient Lactobacillus brevis strain. Since different microbial strains exhibit markedly different glutamate decarboxylase activities, the choice of strain can dramatically influence GABA yield during fermentation. Thus, fermentation efficiency, rather than the fruit's inherent GABA content, is the key determinant of the final GABA concentration in the beverage. Additional factors that may affect GABA accumulation include the composition of the fermentation medium, which in this case is different types of juices with their own endogenous sugars, organic acids, and amino acids. Also, the endogenous GABA content of the used variety/genotype could be important, since as demonstrated in Table 1, different varieties from the same species could differ significantly in their GABA content.

In addition, it should be noted that fermentation does not always lead to high-GABA beverages. Studies with kombucha-type beverages, for example, indicate that albeit fermented, they contain low-to-moderate amounts of GABA and polyphenols [153,154].

5.2. Optimization of Culture Conditions for GABA Production

Numerous studies have investigated strategies to enhance GABA yield by optimizing key fermentation parameters, including the initial pH of the culture medium, fermentation temperature and duration, concentrations of L-glutamic acid and pyridoxal-5′-phosphate (PLP), and the addition of various media components.

The pH of the culture medium is a critical determinant of GABA biosynthesis in LAB because it influences both bacterial growth and glutamate decarboxylase (GAD) activity [135]. Several strains, including *L. brevis* NCL912, *L. paracasei* NFRI 7415, and *L. buchneri*, show optimal GABA production at pH 5.0 [156–158], whereas *L. brevis* GABA100 reaches maximum yield at pH 3.5 during black raspberry juice fermentation [94]. Overall, LAB generally perform best between pH 3.5 and 5.0 [94]. As pH naturally declines during fermentation, active regulation can be necessary, as shown for *S. salivarius* subsp. *thermophilus* Y2, where periodic adjustment to pH 4.5 improved production [159]. Species variability also exists; for example, *P. pentosaceus* MN12 achieves peak GABA output at pH 7 [160]. Since extreme pH conditions can inactivate GAD, maintaining an optimal range is essential [161].

Temperature likewise affects GABA synthesis. *L. plantarum* FRT7 performs better at 30 °C than at 40 °C [162], while *P. pentosaceus* MN12 shows optimal production at 45 °C [160]. Many *L. plantarum* strains reach maximal yields at 30–37 °C [145,163,164], and GAD activity in *L. brevis* 9530 increases with temperature [165]. Additional studies indicate peak GAD activity in *L. plantarum* at 40 °C, pH 4.5, and in *L. sakei* at 55 °C, pH 5 [166,167]. Fermentation duration also plays a decisive role. For instance *L. plantarum* achieved peak output in 35 h, and *Levilactobacillus brevis* reached maximum GABA levels within 30 h [168,169].

GAD activity, and thus GABA yield, is regulated by several interdependent factors, including pH, temperature, PLP availability, and L-glutamic acid supplementation. Because LAB cannot produce sufficient L-glutamic acid, monosodium glutamate (MSG) is typically added as a precursor. Moderate MSG levels enhance GABA formation, whereas excessive concentrations inhibit growth and reduce yield [170]. Optimal MSG levels vary widely: *L. plantarum* FBT215 shows maximal production at 50 mM MSG [163], *L. brevis* CRL 1942 at 270 mM MSG [171], and *L. brevis* CRL 2013 can produce 265 mM GABA with >99% molar yield in modified MRS broth [142]. Transcriptomic data indicate that MSG also upregulates enzymes involved in carbohydrate, fatty acid, and amino acid metabolism, promoting higher GABA biosynthesis.

PLP is an essential GAD cofactor and strongly influences GABA production [156,162]. Beyond PLP, factors such as Tween-80 concentration, metal ions, and the choice of carbon and nitrogen sources can further enhance GAD activity [135,172]. For example, adding 4% maltose increased GABA production by 16% in *L. brevis* K203 [173], while 1.5% galactose boosted levels by 38.6% in fermented adzuki bean milk [174]. Glucose has also been shown to effectively enhance L-glutamic acid formation without additional supplements [175], highlighting the potential of carbohydrate additives to improve GABA yields.

6. Limitations of the Study and Concluding Remarks

6.1. Limitations of the Study

6.1.1. Predefining GABA and Polyphenol Content in Functional Beverages

Reviewed studies report considerable variation in the polyphenol and GABA content of different beverages, underscoring the need for a more standardized framework for evaluating their functional potential. For the purposes of this review, and to enable more meaningful comparison, we define functional beverages as those that provide at least 200 mg of GABA and 500 mg of polyphenols per single 200 mL serving. These thresholds

are not formal dietary reference values; rather, they are pragmatic estimates informed by the limited available data on dietary intake and by levels plausibly associated with potential health benefits. As discussed in Section 2 of this review, GABA is considered safe with very low toxicity even if administered in high doses exceeding 5, however, the typical GABA intake with the diet rarely exceeds 700 mg daily. The daily intake of polyphenols differs in different parts with a maximum daily intake estimated to approximately 1800 mg/day. Based on these intake ranges and on the premise that functional foods should provide health benefits beyond basic nutrition, we consider the proposed benchmark values to be diet-relevant and appropriately balanced—not excessively high, yet not too low to confer meaningful physiological effects.

6.1.2. Considering Total Polyphenol Content, Instead of Individual Constituents

Another limitation of the selected approach is that we consider total polyphenol content, rather than specific phenolic compounds, as a criterion for potential health benefits. It is well established that the in vivo effects of polyphenols depend largely on their bioavailability, which encompasses their absorption, transport, distribution, and retention in biological fluids, cells, and tissues. Understanding bioavailability is essential for linking dietary intake to plasma and tissue concentrations of bioactive metabolites and, ultimately, to potential health outcomes [176]. Bioavailability varies widely among polyphenols; the most abundant dietary compounds are not necessarily the most bioavailable. Once absorbed, polyphenols undergo methylation, sulfation, and glucuronidation. For example, catechol-*O*-methyl transferase methylates compounds such as quercetin, catechin, caffeic acid, and luteolin, and cyanidin is methylated to peonidin in humans [177]. Plasma concentrations, typically in the nM to low μM range, reflect bioavailability and differ by compound and food source. Among aronia polyphenols, catechin and quercetin are absorbed more efficiently than anthocyanins, which appear at very low plasma levels [178]. Another example is proanthocyanidins, which, unlike most plant polyphenols, are high-molecular-weight polymers. Thus, oligomers larger than trimers are generally not absorbed in the small intestine, as shown in multiple animal and human studies [178]. Nevertheless, total polyphenol content remains a useful indicator of antioxidant capacity, which may exert meaningful local effects in the gastrointestinal tract—the first site of exposure following ingestion. Moreover, using total polyphenol content provides a clearer and more practical framework for the aims and scope of the present review.

6.1.3. Considering Only GABA and Polyphenols as Bioactive Components

Functional foods may contain a wide variety of bioactive compounds that provide diverse health benefits. For example, carotenoids such as β-carotene, lutein, and lycopene act as potent antioxidants and have been associated with improved eye health, enhanced immune function, and a reduced risk of certain cancers [179]. Thus, tomato juice could have additional health benefits, related not only to GABA and polyphenols, but to carotenoids, for example. Similarly, bioactive peptides derived from fermented foods have been shown to possess antihypertensive and immunomodulatory effects [180]. Given this diversity, focusing solely on GABA and polyphenols may limit the potential health benefits of functional beverages. Incorporating a broader range of bioactive compounds could provide a more comprehensive approach to health promotion, but would result in unfocused and untargeted studies.

6.2. Concluding Remarks

In this review, we adopted a standardized framework in which a single 200 mL serving of a functional beverage should ideally provide at least 200 mg of GABA and 500 mg of polyphenols. Although these target values are informed by current scientific

evidence, achieving such concentrations in a single serving without fortification remains a substantial challenge. Our comprehensive literature analysis indicates that no currently available beverages meet both criteria simultaneously. Nonetheless, the development of functional beverages enriched in GABA and polyphenols can be feasible through the following complementary approaches, each with distinct advantages and limitations:

1. Sourcing fruits and vegetables with naturally high GABA and polyphenol content.

Natural sources of GABA, such as tomato and lychee, provide relatively high concentrations compared to most other fruit and vegetable juices. Tomato juice, in particular, can deliver approximately 200 mg of GABA in as little as 20–30 mL, making it highly effective for functional beverage applications. However, these high-GABA sources generally contain only moderate polyphenol levels, limiting their contribution to antioxidant capacity. Conversely, polyphenol-rich juices, including black chokeberry, black currant, elderberry, and blueberry, contain minimal GABA. While this approach is straightforward and relies on unprocessed raw materials, it cannot simultaneously deliver high levels of both GABA and polyphenols in a single serving, necessitating the exploration of complementary strategies.

2. Mixing fruit and vegetable juices with complementary profiles.

Blending juices with complementary GABA and polyphenol content provides a practical strategy to overcome the limitations of individual sources. For instance, combining GABA-rich tomato or lychee juice with polyphenol-rich black chokeberry or blueberry juice can produce a beverage that provides both 200 mg of GABA and 500 mg of polyphenols per serving. This approach enables precise tailoring of nutrient composition while maintaining manageable serving sizes. The primary challenge lies in sensory optimization, as blending can affect taste, aroma, and color. Formulations must balance functional benefits with palatability to ensure consumer acceptance.

3. Addition of medicinal plants to enhance polyphenol content.

Incorporating small amounts of medicinal plants, such as Camellia sinensis, sage, or lemon balm, can substantially increase polyphenol content while contributing minimally to GABA. Typically, additions of 2–4 g per serving are sufficient to improve antioxidant capacity, flavor complexity, and color stability through copigmentation with anthocyanins. Medicinal plants can also mask undesirable bitter or astringent notes, enhancing overall palatability. However, excessive inclusion may negatively impact sensory quality, and their contribution to GABA is negligible, rendering them unsuitable as the sole strategy for achieving functional GABA targets. Careful selection of plant species and optimization of dosage are, therefore, critical to maximize benefits without compromising flavor.

4. Fermentation of fruit and vegetable juices with lactic acid bacteria and MSG.

Fermentation with selected lactic acid bacteria (LAB) strains in the presence of monosodium glutamate (MSG) represents the most effective approach for producing beverages with very high GABA concentrations. The efficacy of this approach depends on strain selection, fermentation conditions, and substrate composition. While fermentation can achieve target GABA levels in small beverage volumes, polyphenol content typically remains moderate. To address this limitation, fermentation of polyphenol-rich juices, such as black chokeberry, elderberry, blueberry, rosehip, black raspberry, or blackberry, is recommended. Additionally, residual MSG may be undesirable for clean-label products, requiring careful optimization to maximize MSG conversion, ensure sensory quality, and maintain compliance with food labeling standards.

Formulating beverages that deliver an optimal balance of GABA and polyphenols without relying on fortification remains a significant technological challenge and represents an important direction for future research. Future studies should prioritize the optimization

of ingredient selection, blending strategies, and processing methods to develop beverages capable of achieving the GABA and polyphenol contents defined in the present review, while maintaining high sensory quality and consumer acceptability.

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